Electric Power Systems Research 111 (2014) 52–61

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Spatio-temporal statistical identification methodology applied to wide-area monitoring schemes in power systems

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A R T I C L E   I N F O

Article history:
Received 26 October 2013
Received in revised form 20 January 2014
Accepted 29 January 2014
Available online 2 March 2014

Keywords:
Biorthogonal decomposition
Correlation matrix
Oscillations
Separability
Wave motion monitoring

A B S T R A C T

Detection and characterization of the dynamic phenomena that arise when the power system is subjected to a perturbation become a significant problem. Therefore, a great deal of attention has been paid to identify oscillatory activity in interconnected power systems through the use of wide-area monitoring schemes. This paper presents a method for detection of propagation features from wide-area system measurements through its traveling and standing components, exploring the relationship between complex modes and the wave motion. The method consists in a biorthogonal decomposition considered from a statistical perspective which has the potential to be applied for wide-area monitoring and analysis using real-time synchronized measurements recorded from power systems. Although the technique is general, data obtained from global positioning system (GPS)-based multiple phasor measurement units (PMUs) from a real event in power systems are used to examine the potential usefulness of the proposed methodology. Furthermore, the decomposition technique based on optimal persistent patterns (OPPs) for time-varying fields is used to validate the applicability of the method.

1. Introduction

Statistical models have been widely used in many engineering and science applications for the analysis of space–time varying system response from measured data; e.g., unsteady fluid flow, turbulence, optimal control, structural dynamics, heat transfer and system identification have been reported [1,3–10,13,15–17,19,20,23–28,30,31,34,37–40,42]. These methodologies use statistical techniques that capture various forms of spatio-temporal variability, such as empirical orthogonal function (EOF), principal interaction pattern (PIP), principal oscillation pattern (POP), optimal persistent pattern (OPP), and canonical correlation analysis (CCA) [4,5,8,10,16,17,19,23–26,28,38–40,42]. Underlying issues of these techniques, such as the estimation of propagating and standing features that may be associated with observed or measured data and their applications to space–time varying processes do not seem to be recognized or, at least, they have not been reported. This fact motivates the derivation of a model based on statistical techniques to identify the behavior of the system to be dealt with. In [3,9,42], local models of spatio-temporally complex fields are used for the study and detection of propagating features in space–time varying processes using a biorthogonal decomposition which splits a space–time varying field into a weighted linear sum of orthogonal spatial and temporal modes. When simultaneously measured responses throughout an interconnected power system are available, modal behavior should be extracted using correlation techniques rather than individual analysis of the system response. This provides a global picture on the system behavior and enables statistical characterization of the observed phenomena which are used for the monitoring and analysis of local and inter-area electromechanical oscillations in power systems. In this paper, we provide a spatio-temporal decomposition technique based on the use of time synchronized measured data recorded by multiple phasor measurement units (PMUs) in power systems to cope with increasing complexity of information in the use of wide-area monitoring schemes. The methodology is proposed to identify and to extract dynamically independent spatio-temporal patterns using a biorthogonal decomposition based on the complex EOF analysis and the separability of complex correlation functions. This approach provides an efficient and accurate way to compute standing and propagating features of general nonstationary processes identifying important information for the analysis of dynamic phenomena in power systems. Moreover, this may lead to greater understanding of the mechanism generating the measured data and lead to better prediction and understanding of the oscillatory activity in

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0378-7796/$ – see front matter
http://dx.doi.org/10.1016/j.epsr.2014.01.024

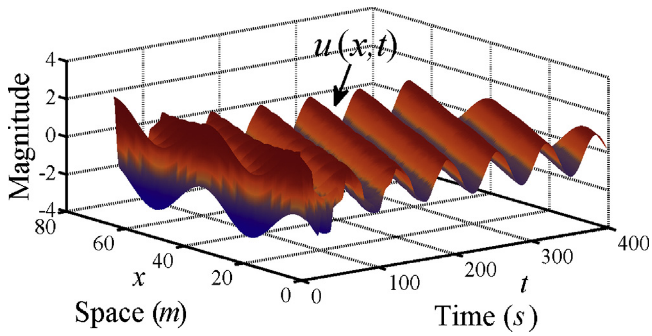

Fig. 1. Conceptual diagram illustrating the phenomenon of the spatial and temporal energy distribution on a space–time varying field.

interconnected systems. The method allows the introduction of several measures that define moving features in space–time varying fields, such as spatial amplitude and phase function, temporal amplitude and phase function, spatial and temporal energy, wave number, angular frequency and average phase speed which can be used for monitoring electrical and electromechanical stability margins implementing the wide area measurement systems (WAMS), and for preventing or controlling instability in large power systems. This decomposition is viewed as the time–space-symmetric version of the Karhunen–Loève expansion or also called complex EOF analysis. As illustrative case, a four-machine two-area test system is presented to examine the potential of the proposed technique. Additionally, undamped oscillation data in power systems recorded by GPS-based multiple PMUs from a real event in the northern systems of the Mexican interconnected system (MIS) [29–31] are used to validate the ability of the method to characterize the electromechanical oscillatory dynamics of interconnected power systems. The obtained results from the proposed method are compared for simplicity with the decomposition technique of OPPs for time-varying fields [10], particularly, in the determination of a set of patterns that optimize a measure of decorrelation for longest time. However, other approaches can be used to characterize modal behavior that require large analytical formulations or that are based on a single data set [1,7,17,23–26,40].

2. Treatment of spatio-temporal data

In order to analyze oscillatory dynamics in a wide-area distribution system, we note that the relationship between spatial and temporal behavior in spatio-time varying fields can be obtained by mapping the spatio-temporal information into a space and time grid, i.e., each component $u(x, t)$ of the space–time varying field is represented by the field value at time and spatial position x [30]. Fig. 1 provides a conceptual representation illustrating that the relationship between spatial and temporal variability in a space–time varying field is conveniently represented by a two-dimensional array [3,9].

Using the above notion to introduce more general ideas, we assume that a data set recorded from measurements or numerical simulations of a power system is available at n spatial locations defined by x_j, $j = 1, 2, \ldots, n$ at N instants in time, t_k, $k = 1, 2, \ldots, N$, which can be represented by an $n \times N$-dimension matrix,

$$\mathbf{X}(x_j, t_k) = \begin{bmatrix} u(x_1, t_1) & \cdots & u(x_n, t_1) \\ \vdots & \ddots & \vdots \\ u(x_1, t_N) & \cdots & u(x_n, t_N) \end{bmatrix}, \text{ where typically, } n \neq N,$$

so that $\mathbf{X}$ is generally rectangular; the rows of this matrix capture the spatial information, while the columns capture the temporal information [29,30]. On the following sections, the theoretical fundamentals of empirical orthogonal functions which represent the bases of the proposed methodology are presented. Most of the notation is standard, vectorial quantities are denoted by boldface letters and scalar quantities by italic letters. Other symbols used are defined in the text.

3. Background of the EOF method

The fundamental idea of the EOF analysis is to find a basis $\boldsymbol{\varphi}$ for linear, infinite-dimensional Hilbert space $\boldsymbol{L}^2([0, 1])$, that maximizes the averaged projection of the response matrix $\mathbf{X}(x, t)$, suitably normalized [18]. The corresponding function for the constrained variational problem is solved and reduced to:

$$\int_0^1 \left[\int_0^1 \langle u(x)u^*(x^|)\rangle \varphi(x^|)dx^| - \lambda\varphi(x) \right]^* \psi^*(x)dx = 0 \tag{1}$$

where the $(^*)$ denotes the conjugate transpose (sometimes denoted as Hermitian, H) and the $(^|)$ denotes transpose vector. Thus, if $\boldsymbol{\psi}^*(x) = 0$, the optimal basis are given by the eigenfunctions φ_j of the integral equation

$$\int_0^1 \langle u(x)u^*(x^|)\rangle \varphi(x^|)dx^| = \lambda\varphi(x), \tag{2}$$

whose kernel is the averaged autocorrelation function $\langle u(x)u^*(x)\rangle \overset{def}{=} \mathbf{C}(x, x^|)$. Under this assumption, the integral (2) can be written as

$$\mathbf{C}\boldsymbol{\varphi}(x) = \boldsymbol{\lambda}\boldsymbol{\varphi}(x) \tag{3}$$

where the resulting autocorrelation matrix $\mathbf{C}$ is a real, symmetric, positive and semi-definite matrix. Therefore, the optimization problem can be recast as the problem of finding the largest eigenvectors $\boldsymbol{\varphi}$ of Eq. (3), called empirical orthogonal functions (EOFs); the corresponding eigenvalues are real, nonnegative, and ordered so that $\lambda_1 \geq \lambda_2 \geq, K, \geq \lambda_j \geq 0$ [18]. This method, also called conventional EOF analysis, cannot be used to detect propagation features due to the assumption that each field is represented as a spatially fixed pattern of behavior and lack of phase information, becoming prohibitive to practical applications [2,12,29].

Now, if we assume that $\boldsymbol{\psi}^*(x) \neq 0$, then (1) can be rewritten as

$$\int_0^1 \int_0^1 \varphi^*(x^|)\langle u(x)u^*(x^|)\rangle \psi^*(x)dx^|dx = \int_0^1 \varphi^*(x)\lambda\psi^*(x)dx \tag{4}$$

such that, the inner product $(\boldsymbol{\varphi}^*(x)\mathbf{C}\boldsymbol{\psi}^*(x)) \neq 0$, with orthogonal eigenvectors $\boldsymbol{\varphi}$, $\boldsymbol{\psi}$, i.e.,

$$\varphi_i\varphi_j = \begin{cases} 0, & i \neq j \\ \delta(\varphi), & i = j \end{cases} \quad \text{and} \quad \psi_i\psi_j = \begin{cases} 0, & i \neq j \\ \delta(\psi), & i = j \end{cases}$$

From (1) it can be seen that if there exists an arbitrary variation (spatial), $\boldsymbol{\psi}^*(x) \neq 0$, then the original field can be reconstructed using two optimal orthogonal basis $\boldsymbol{\varphi}$, $\boldsymbol{\psi}$, given from (4). Based on this notion, an efficient technique to find the optimal basis using complex EOF analysis (CEOFs) is proposed in the next section.

4. Proposed methodology

Consider that measured data were recorded from a power system network during an oscillatory activity. In general, the dynamic phenomena that arise when the power system is subjected to a perturbation can be represented by

$$\mathbf{X}(x, t) = \mathbf{X}_{swc}(x, t) + \mathbf{X}_{twc}(x, t) \tag{5}$$

where $\mathbf{X}_{swc}$ and $\mathbf{X}_{twc}$ denote the standing and traveling wave components that can be associated with electromechanical oscillations in power systems.